LIQUID OXYGEN IN AIRCRAFT[1]

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In passenger aircraft flying above 10,000 ft. large quantities of oxygen have to be carried for breathing purposes. An important reduction in weight can be effected by carrying the oxygen supply in the form of liquid, rather than in gas cylinders. It is then necessary to provide means of evaporating the liquid. Various methods of evaporation are discussed, and the liquid-oxygen evaporator developed at the University of Toronto for the Royal Canadian Air Force is described. In this apparatus the heat of evaporation is obtained from the surrounding atmosphere, and the gas pressure is automatically controlled, so that the rate of supply of gas is determined by demand. Successful test flights have been carried out, including one journey across the Atlantic.

I. INTRODUCTION

The importance of oxygen in high-altitude flight is well known. At altitudes greater than 10,000 ft. the partial pressure of oxygen in normal atmospheric air is insufficient to maintain a human being at full efficiency, except after slow acclimatization. At 25,000 ft. the amount of oxygen is not enough even to support life in the average unacclimatized individual. The problem of supplying the crew and passengers in an aircraft with the requisite amounts of oxygen can be met either by means of a pressurized cabin or by supplying added oxygen directly to the individuals through face masks. Ideally, the pressurized cabin is the preferable solution, since it eliminates other physiological effects of the reduced pressure, as well as that of the lack of oxygen. However, there are obvious objections to the use of pressurized cabins in military aircraft, and even in the transport of passengers the use of oxygen masks is not likely to disappear entirely for some years to come.

In nearly all existing aircraft the oxygen supply is carried in the form of compressed gas in steel cylinders. The weight of the cylinders is five to six times that of the contents, and in large aircraft the weight and bulk become formidable. To take a moderate example, imagine an aircraft carrying twenty-five persons on a flight where provision must be made for a period of 6 hr. at 10,000 to 20,000 ft. At 20,000 ft. the average amount of oxygen required per person is 2 liters per minute (N.T.P.), so that the total amount necessary is 18,000 liters. Allowance being made for the unavailable residue in the cylinders, this requires twenty-two oxygen cylinders of the standard U. S. aircraft type. These make a dead weight of equipment of 396 lb. (exclusive of supporting brackets) and occupy a space of 27 cu. ft.

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II. THE USE OF LIQUID OXYGEN

If the oxygen supply is in the liquid form instead of as compressed gas, a much greater amount can be carried in a given container. At the same time high pressures are not necessary, and lighter containers can be used. Liquid oxygen is preferably stored and transported in metal vacuum flasks, to reduce loss by evaporation. The ratio of the weight of the container to that of the contents is about 2 to 3. However, before it can be used for breathing purposes, the liquid oxygen has to be evaporated, and warmed to a reasonable temperature. In the above example, with a total gas consumption of 50 liters per minute, a heat supply of 150 watts is required for the evaporation alone. This is very much greater than the natural leakage of heat into a properly designed vacuum flask, and a supply of heat must be provided. The evaporator adds to the equipment necessary, but the weight ratio can still be kept at 1 to 1 or better.

The idea of using liquid oxygen for this purpose is by no means new. An experimental, one-man, liquid-oxygen unit was designed by Siebe and Gorman in Great Britain about 1918. However, several factors have prevented it from coming into general use. The early liquid-oxygen evaporators were not entirely fool-proof and required a certain amount of attention in flight. There was danger of the oxygen supply failing, with disastrous consequences. Further, liquid oxygen is always subject to loss by evaporation. In a 25-liter vacuum flask the rate of loss is usually 1 to $1\frac{1}{2}$ liters per day, and it is not economical to store the liquid for longer than about 1 week. This means that it would be necessary to maintain fresh supplies of liquid oxygen at all stopping places. At busy airports, close to large centers of population, this would not be difficult, but it would be a serious problem if the supply had to be maintained at all military airfields. Until the beginning of World War II very few large aircraft were operating regularly at oxygen altitudes, and the saving in weight which could be effected by the use of liquid oxygen was not important enough to overcome these disadvantages. Consequently, experiments on the use of liquid oxygen were abandoned long before 1939, and the use of compressed gas became standard both in the United Nations and in the enemy countries.

Interest in the possibilities of liquid oxygen was revived, both in the United States and in Canada, when large passenger and troop-carrying aircraft were developed, and the prospect arose of using these aircraft on long flights in which it would be necessary to fly at oxygen altitudes, on account of weather conditions or mountainous country. Such flights would take place mainly over established routes, where supplies of liquid oxygen could be arranged if necessary.

When the Royal Canadian Air Force asked the authors to investigate the possibilities of liquid oxygen, it was with this type of service in mind, and the following general requirements were laid down: The liquid-oxygen unit, comprising vacuum container and evaporator, must provide oxygen for twenty-five persons at 20,000 ft. continuously for several hours and, if possible, without attention in flight. At the same time it must be capable of meeting wide variations in demand, with changes in altitude and changes in the breathing rates of individuals. It should allow for an overload of at least twice the normal rate of consumption for short periods, in order to meet the most extreme conditions possible in the aircraft for which it was designed. In order that the liquid-oxygen unit could be used with other standard oxygen equipment,—for example, with R. C. A. F. demand valves,—and be reasonably interchangeable with a compressed-gas system, the oxygen gas must be delivered at a pressure of not less than 25 p.s.i. The evaporator must, of course, continue to deliver gas when the aircraft is subject to acceleration, and when the ambient temperature is as low as −40°C.

The design problem concerns mainly the evaporator and any necessary controls. There are two general methods which might be used to supply the necessary heat,—direct heating by an electric heater immersed in the liquid, or an evaporator separate from the container. Direct electrical heating has been used in a liquid-oxygen unit designed by Mathis and Milan (2) for use in hospitals, and later modified for aircraft. This is the simplest method, but in aircraft application there are objections to the amount of power required and to the fact that the vital oxygen supply is dependent on the maintenance of the electrical power system. Control of the average rate of supply of gas is simple, but an overload results in a drop of gas pressure unless it is soon compensated by increasing the current through the heater.

The special advantage of the separate evaporator is that the heat necessary can be obtained from the surrounding atmosphere, since the temperature of the liquid oxygen is far below the lowest possible atmospheric temperature. The original Siebe–Gorman unit made use of an atmospherically heated external evaporator; the same principle is applied in a unit designed by Akerman (1) and in the unit to be described below. In this type of evaporator the maximum rate at which gas can be supplied depends on the amount of heat which can be absorbed from the surroundings. This may be severely limited by the coating of frost which inevitably forms on the cold evaporator coils.

III. THE UNIVERSITY OF TORONTO–R.C.A.F. LIQUID-OXYGEN UNIT

Figure 1 illustrates the principle of the liquid-oxygen unit designed at the University of Toronto for the R. C. A. F. The container (F) is a 25-liter metal vacuum flask of the usual commercial type. To this the evaporator head and automatic controls are attached. "On-off" valves, master switches, pressure gauges, and the dial of an electrical contents gauge are mounted on a panel accessible to one of the crew. The complete unit weighs 67 lb. empty, and holds 63 lb. of liquid oxygen, producing 19,500 liters of gas, with allowance for the small unusable residue. There is therefore a saving in weight of over 300 lb., as compared with the equivalent in compressed-gas cylinders. At the same time the liquid-oxygen unit occupies a space of only 7 cu. ft.

In order to operate the unit, the flask is filled with liquid oxygen and sealed from the atmosphere, so that the pressure can build up in the space above the liquid, until the required operating pressure is attained (25 to 35 p.s.i. for R. C. A. F. equipment). The operating pressure is the difference between the vapor pressure of the liquid oxygen and the pressure of the surrounding atmosphere. Therefore the temperature of the whole mass of liquid must be raised until it is in equilibrium at the desired pressure. UU in the figure is the evaporator, connected to the liquid oxygen outlet pipe (O), which extends nearly to the bottom of the flask. If the pressure in UU is a little less than that in F, liquid oxygen is forced into the evaporator coils, where it is evaporated by absorption of heat from the atmosphere. The gas leaves the evaporator several degrees colder than the ambient temperature, but by the time it has passed also through several feet of distribution manifold it is warm enough to be breathed.

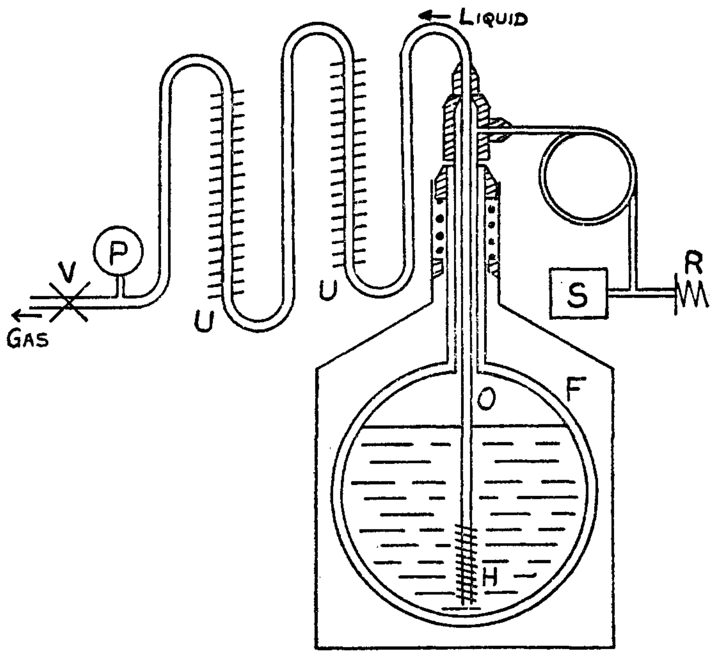

FIG. 1

In a properly insulated vacuum flask of 25 liters capacity the natural heat leak is sufficient only to raise the vapor pressure at a rate of about 1 p.s.i. per hour. Therefore, in order to attain the required operating pressure in a reasonable time, heat must be supplied. Incidentally, it should be noted that the very slow increase of pressure caused by the natural heat leak permits a storage period of 24 to 36 hr. during which there is no loss by evaporation. In order to build up and maintain the operating pressure, an electric heater (H) is wound upon the bottom end of the outlet pipe. This heater is controlled by a pressure-operated switch (S), so that it is turned on automatically whenever the pressure falls below the safe minimum. This, and a spring-loaded relief valve (R), keep the gas pressure between fixed limits as long as the unit is in operation.

The flow of gas is controlled entirely by the various outlet valves in the gas delivery manifold beyond the main control valve (V), for liquid is transferred from the container to the evaporator only as gas is drawn off. Thus the complete system functions as a supply of gas under a suitably controlled pressure, delivering oxygen on demand, up to the maximum capacity of the evaporator.

The evaporator proper consists of two sections (UU) of finned copper tubing, ventilated by means of a small fan or by an air scoop in the side of the aircraft. It will evaporate up to 150 liters of gas per minute, even when the coils are heavily frosted, and when the ambient temperature is as low as $-40°C$. With higher rates of consumption of oxygen, the liquid tends to surge in the liquid outlet pipe (O) and to splash over from the evaporator into the gas manifold.

At the normal rate of oxygen consumption, 50 to 75 liters per minute, the vapor pressure in the container remains quite steady for several hours at a time, and for normal operation the automatic control of the heater is not essential. However, there is a tendency for the gas pressure to decrease slowly under high rates of consumption, or when the container is nearly empty, and the automatic control is a safety feature. Since the heater is on only during the preflight servicing, and at rare intervals in flight, the drain on the electric power supply of the aircraft is unimportant.

It is interesting to note that the nearly constant pressure is the absolute vapor pressure in the container. Therefore, as the aircraft ascends and the surrounding atmospheric pressure decreases, the gauge pressure of the gas supply increases by an equal amount. This reduces the time required to generate the operating pressure before flight, since a gauge pressure of 21 p.s.i. on the ground will produce an operating pressure of 25.6 p.s.i. at 10,000 ft. On the other hand, this sometimes causes a small wastage of oxygen, since the relief valve may open during an ascent.

IV. TRIALS

Liquid-oxygen units of the type described have been tested on several long flights, culminating in a Transatlantic flight in November, 1944. For this flight two units were installed in the aircraft, and used alternately, in order to provide a sufficient total supply for the longer non-stop legs of the journey. Seven persons actually obtained their oxygen supply from the liquid-oxygen system, breathing through R. C. A. F. demand valves. In addition, whenever the aircraft was at oxygen altitudes, the correct amount of oxygen for twenty-two resting passengers was allowed to blow away. Owing to strong head winds the journey required 24½ hr. of flying time, spread over an elapsed period of 72 hr. Altogether, a period of 15 hr. and 21 min. was spent at oxygen altitudes, mainly at 20,000 ft. The liquid-oxygen system delivered gas continuously whenever necessary, with practically no attention in flight beyond the turning of the taps and switches necessary to alternate units when a container was empty. Thus it was demonstrated in a most satisfactory manner that a liquid-oxygen system is feasible for large aircraft.

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REFERENCES

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